Propagation of Low-Frequency, Transient Acoustic Signals through a Fluctuating Ocean: Development of a 3D Scattering Theory and Comparison with NPAL Experimental Data

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LONG-TERM GOALS

Development of a new, 3D, modal theory of low-frequency, long-range sound propagation through a fluctuating ocean, including both CW and transient acoustic signals.

Comparison of theoretical predictions with NPAL experimental data.

OBJECTIVES

To develop a 3D modal theory of broadband sound propagation though a fluctuating ocean, including analysis of the coherence function for transient acoustic signals and temporal coherence.

To develop computer codes for calculation of the horizontal and vertical coherence functions of transient acoustic signals and temporal coherence.

To compare theoretical predictions with the 1998-1999, 2004, and 2009-2011 (in the Philippine Sea) NPAL experimental data.

APPROACH

Coherence of low-frequency sound waves propagating in the ocean diminishes due to sound scattering by internal waves (IWs), spice, and other ocean processes. Therefore, studies of statistical characteristics of low-frequency sound waves propagating through a fluctuating ocean are important for many practical applications, e.g., underwater communication and assessment of performance of

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modern acoustic sensor arrays. With the support of our previous and current ONR grants, we have been developing a new, 3D, modal theory of sound propagation in a fluctuating ocean which is applicable for both CW and transient signals. Based on this theory, efficient numerical codes for calculation of the statistical characteristics of acoustics signals have been developed. Temporal coherence of acoustic signals, horizontal and vertical coherence functions, sound scattering into refractive shadow zone, evolution of cross-mode coherences and mode intensities with range, and the mean sound field have been calculated and analyzed in the 3D modal theory. These theoretical predictions have been compared with experimental data obtained by the North Pacific Acoustic Laboratory (NPAL) in the North Pacific in 1998-1999 [1] and 2004 [2], and in the Philippine Sea in 2009-2011 [3]. The results obtained in the 3D modal theory of sound propagation in a fluctuating ocean and comparison of its predictions with experimental data are summarized in Refs. [4-15], including four per-reviewed papers [4-7].

Dr. A. G. Voronovich and Dr. V. E. Ostashev are PI and Co-PI in this project.

WORK COMPLETED

During the reporting period, the following three tasks were completed:

Task 1. The range and frequency dependences of the coherence time of acoustic signals were further investigated with modified computer codes.

Task 2. The vertical coherence of acoustic signals was calculated and analyzed for the 2009 NPAL long-timescale experiment in the Philippine Sea and compared with theoretical predictions.

Task 3. The intensity fluctuations of acoustic signals in the 2009 NPAL long-timescale experiment in the Philippine Sea were calculated and analyzed.

RESULTS

The following results were obtained in FY2012:

Task 1.
Computer codes for calculation of the statistical characteristics of acoustic signals in the 3D modal theory of sound propagation in a fluctuating ocean were further modified. This enabled to extend our previous studies of the coherence time τ_c of narrow-band acoustic signals to higher frequencies. The coherence time τ_c is defined as a value of a time lag for which the temporal coherence function of an acoustic signal decreases by a factor $1/e$. In Fig. 1, the coherence time is plotted versus the propagation range r for several frequencies f ranging from 12 to 300 Hz. (Previous codes allowed us to handle frequencies up to 100 Hz.) In the calculations, the sound-speed profile and Brunt-Väisälä frequency were chosen as the Munk canonical profiles and it was assumed that the ocean depth is 3 km and the source depth is 807 m. Apart from the left-most parts of the curves corresponding to $f = 12$, 25, and 50 Hz, it follows from Fig. 1 that the dependence of τ_c on r can be approximated as $\tau_c \sim r^{-\alpha}$, where a value of the coefficient α slightly changes with range. The legend in the figure provides with the values of α at $r = 10^4$ km; these values are in the range $0.50 \le \alpha \le 0.66$.

Figure 2 depicts the coherence time τ_c versus frequency f for four propagation ranges r. The dependence of τ_c on f can be approximated with $\tau_c \sim f^{-\beta}$, where a value of the coefficient β depends on the frequency range. At $r = 10^4$ km, $\beta = 1.08$ in the range $25 \le f \le 75$ Hz; $\beta = 2.22$ in the range $100 \le f \le 150$ Hz; and $\beta = 3.93$ in the range $150 \le f \le 300$ Hz.

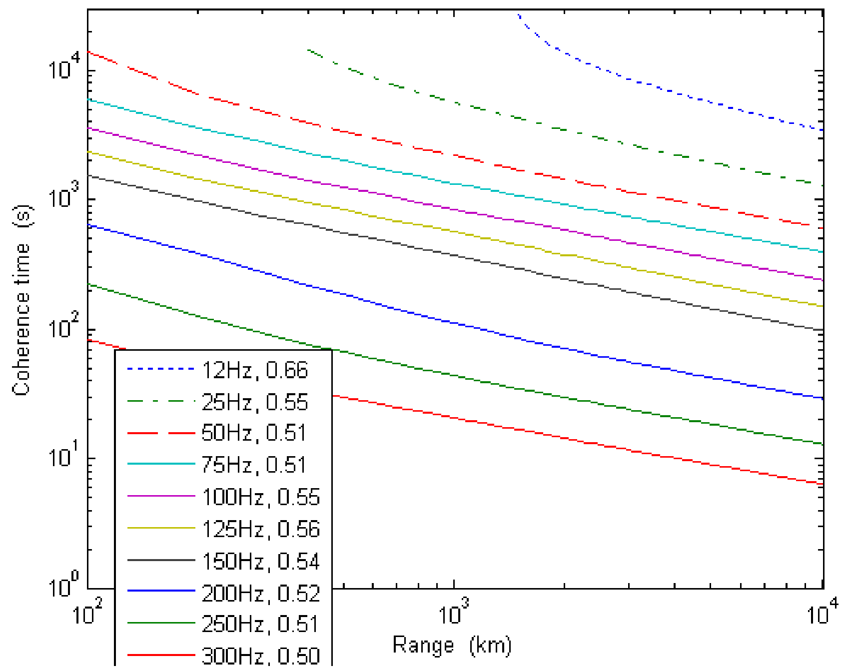

Figure 1. Coherence time of a narrow-band acoustic signal versus propagation range for different frequencies. The sound speed and Brunt-Väisälä frequency correspond to the Munk canonical profiles. The ocean depth is 3 km and the source depth is 807 m.

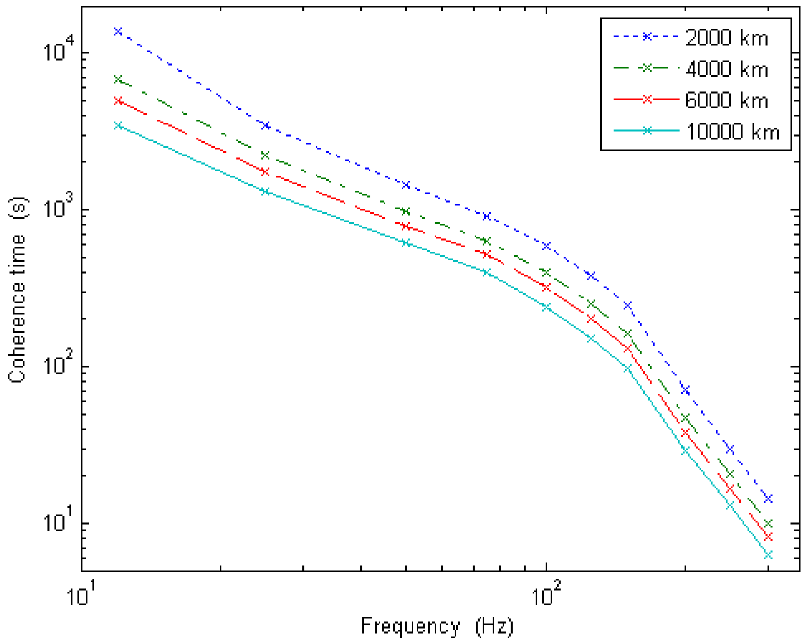

Figure 2. Coherence time of a narrow-band acoustic signal versus frequency for different propagation ranges. The ocean stratification and parameters of the problem are the same as in Fig. 1.

Task 2.
Computer codes were developed to process the data of the 2009 NPAL long-timescale experiment in the Philippine Sea. In the experiment, the 225-325 Hz swept-frequency source was located at the depth of 1050 m and range of 192.8 km from the Deep Vertical Line Array (DVLA). Standard 135 ms acoustic signals were transmitted every 5 min. The recorded signals were filtered in a narrow frequency band of 5 Hz. The upper two plots in Fig. 3 depict the square root of the acoustic intensity integrated over the duration of the filtered signal versus the transmission number at two hydrophones of the DVLA located at the depths of 975 and 1000 m, respectively. It follows from the figure that the integrated intensities significantly change with time and exhibit quasi-periodic oscillations. Temporal evolutions of the integrated intensities are very different at these two hydrophones located only 25 m apart. The lower plot in Fig. 3 shows the cross-correlation of the acoustic signals at these two hydrophones as a function of transmission. Again, significant variations in the cross-correlation are clearly seen. The normalized mean value of the cross-correlation between these two hydrophones is 0.20.

Figure 4 shows an “instantaneous” vertical coherence of recorded acoustic signals obtained for the 65th transmission and for the reference hydrophone located at the depth of 975 m. The vertical coherence has somewhat random behavior which is typical for other transmissions. The vertical coherence averaged over all 92 considered transmissions is plotted in Fig. 5, left plot. In comparison with Fig. 4, the averaged vertical coherence exhibits a regular behavior and, generally, decreases with increasing the vertical separation between hydrophones. The decrease is not monotonic: local maxima and minima are seen in the figure which can be explained by the modal structure of the sound field in the

oceanic waveguide. Similar results were obtained in the 2004 NPAL LOAPEX experiment in the North Pacific.

The right plot in Fig. 5 shows the predictions of the vertical coherence obtained with the 3D modal theory. Comparing two plots in Fig. 5, it can be concluded that the agreement between the theoretical predictions and experimental data is relatively good indicating that the theory captures main features of the vertical coherence. Both the theory and experiment indicate that the vertical coherence radius is of order of 30 m.

Task. 3

Computer codes were developed to calculate the normalized standard deviation (the scintillation index) β of intensity fluctuations along an individual ray in the 2009 NPAL long-timescale experiment. It was shown that for 19 hydrophones of the DVLA shown in Figs. 4 and 5, the value of β is in the range: $0.48 \le \beta \le 0.82$. These values of β indicate that the intensity fluctuations are moderate-to-strong. (For strong intensity fluctuations, when $\beta \sim 1$, an instantaneous value of the sound intensity might significantly deviate from the mean intensity.) This result is consistent with the upper two plots in Fig. 3 which show relatively strong variations of the acoustic intensities at two hydrophones.

IMPACT/APPLICATIONS

Analysis of the range and frequency dependencies of the coherence time of acoustic signals propagating in a fluctuating ocean was extended to higher frequencies. The vertical coherence of acoustic signals in the 2009 NPAL long-timescale experiment in the Philippine Sea was calculated and analyzed. It was shown that theoretical predictions of the vertical coherence obtained with the 3D modal theory agree with experimental results.

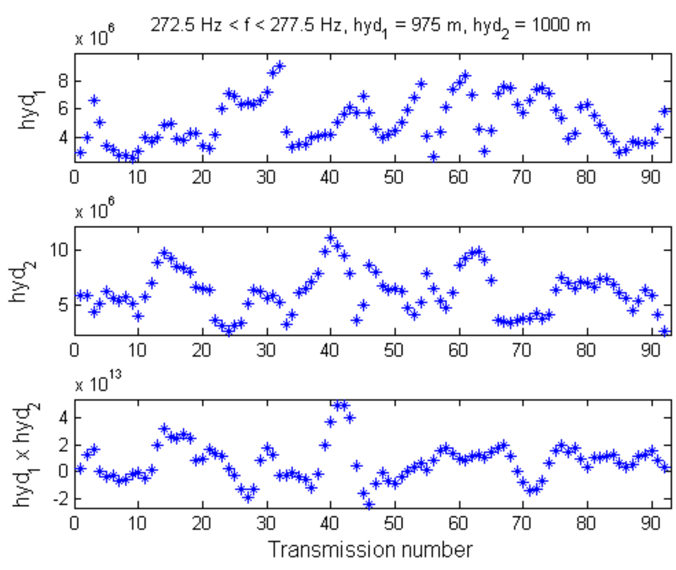

Figure 3. Results of the 2009 NPAL long-timescale experiment in the Philippine Sea. Upper two plots: square root of the acoustic intensity integrated over the duration of the filtered signal versus the transmission number at two hydrophones of the DVLA located at the depth of 975 and 1000 m. Lower plot: the cross-correlation of the acoustic signals at the two hydrophones as a function of transmission.

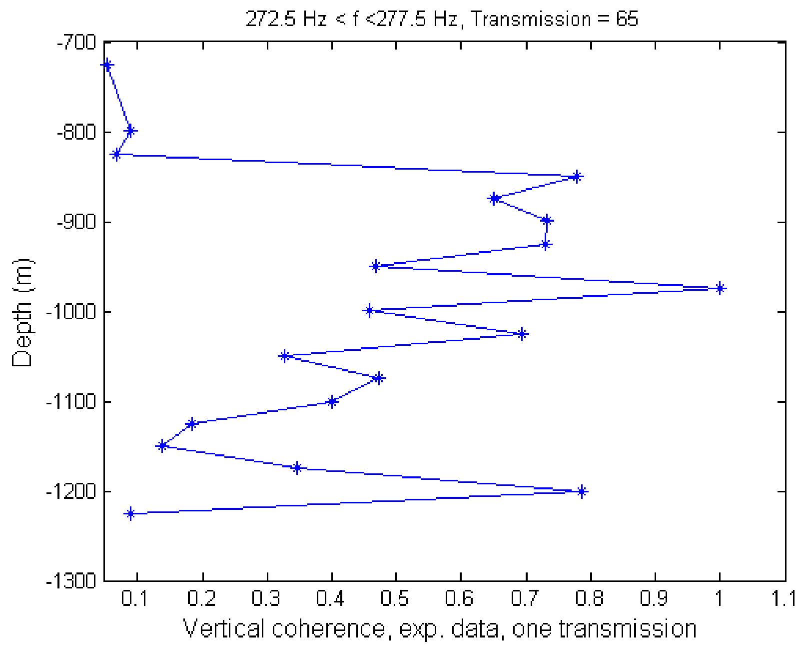

Figure 4. Vertical coherence of acoustic signals in the 2009 NPAL long-timescale experiment in the Philippine Sea. The result corresponds to the 65th transmission and the reference hydrophone located at the depth of 975 m.

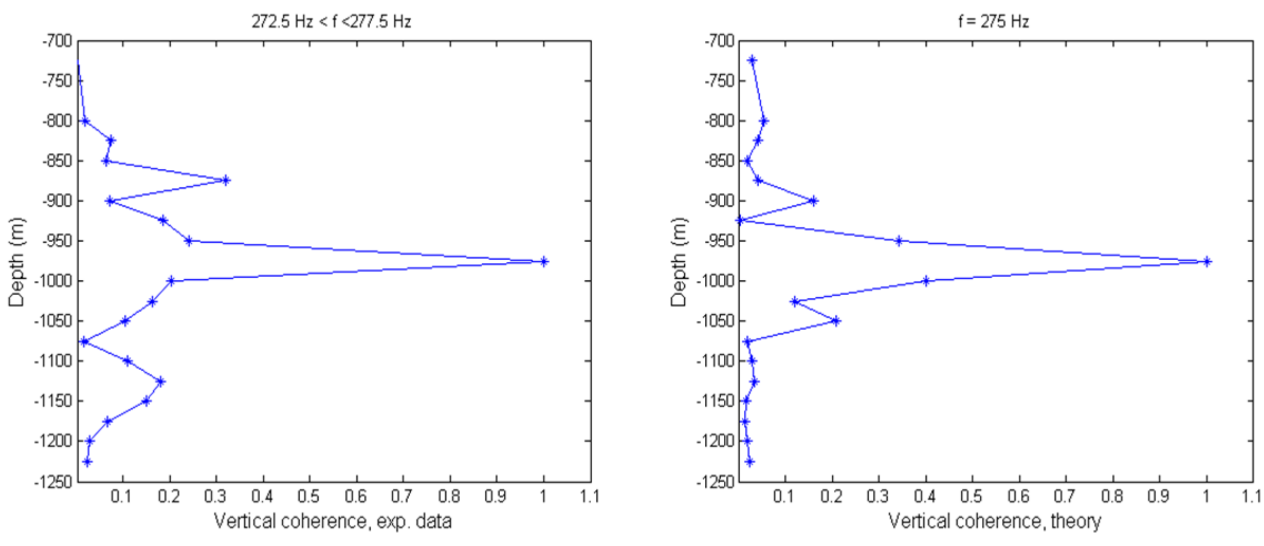

Figure 5. Normalized vertical coherence of narrow-band acoustic signals versus the hydrophone depth for the 2009 NPAL long-timescale experiment in the Philippine Sea. The reference hydrophone is located at the depth of 975 m. Left plot: experimental data. Right plot: predictions obtained with the 3D modal theory.

RELATED PROEJCTS

The 2004 NPAL experiment in the North Pacific [2] and the 2009-2011 NPAL experiment in the Philippine Sea [3].

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